Experiment #3, The Latent Heat of Vaporization of Liquid Nitrogen.

1 Purpose

1. To review the physical concepts and relationships associated with the flow of heat in and out of materials.
2. To determine the specific heat of aluminum in the temperature range between liquid nitrogen (LN_2) and room temperature water.
3. To determine the latent heat of liquid nitrogen (LN_2).
4. To determine the rate of heat flow through a Styrofoam cup when the outer surface of the cup is held at room temperature while its inner surface is maintained at LN_2 temperature.

2 Introduction

When heat energy is added to a substance its temperature usually rises except when a change of phase occurs (e.g., a solid is changed into a liquid phase or a liquid state is changed into its vapor phase). The change of phase occurs without increase or decrease in the substance's temperature. The thermal energy absorbed goes into changing the state of the matter involved. Conversely, when you get a phase change as the temperature drops latent heat must be released. The latent head associated with water vapor in the atmosphere is one of the most significant factors determining the weather. It moderates temperature drops at night. And when released through the formation of water droplets drives the winds associated with storms, think hurricane.

The historical unit of heat energy, the **calorie**, was defined as the amount of heat energy needed to raise the temperature of one gram of water by one degree Celsius. The calorie is now defined in terms of the SI unit of energy, the **joule**, by:

1 cal = 4.184 J

2.1 Specific Heat

When heat flows into or out of an object its temperature changes. The connection between the change in heat energy and the change in temperature is the specific heat. The heat energy ΔQ needed to raise the temperature of a substance is related to its mass according to the formula:

$$\Delta Q = mc\Delta T \quad (1)$$

where ΔQ is the quantity of heat entering the material, m is the mass of the material, c is the specific heat, and ΔT is the change in the temperature of the material. The specific heat c is defined as the heat energy needed to raise the temperature of one gram of a substance by one degree Celsius ($^{\circ}$C). In general, the value of the specific heat of a solid substance is predominantly a function of temperature, though small variation of the specific heat occurs due to variation in pressure or volume. The value of c in Eq. (1) is taken as its average value, $\overline{c}$,over the temperature interval between its initial and final temperatures, T_i and T_f respectively.

The specific heat of substances varies with the temperature, as for example the average value of the specific heat of aluminum is **0.17 cal/g-$^{\circ}$C** between room temperature and liquid nitrogen temperature while it remains essentially constant (0.215 cal/g-$^{\circ}$C) from room temperature to 100 ^{o}C . In contrast to this, the specific heat of water decreases from 1.00728 cal/g-$^{\circ}$C to 0.99795 cal/g-$^{\circ}$C in the temperature range 0 to 35°C and then increases to 1.00697 cal/g-$^{\circ}$C at 100 $^{\circ}$C.

2.2 Latent Heat

Under certain circumstances the heat supplied to (or removed from) the material does not cause a change in the temperature of a substance, instead it causes a change of phase (e.g., boiling, melting, freezing or condensation). The relationship between the heat added and the amount of material that changes from one phase to another is,

$$\Delta Q = L\Delta m \qquad (2)$$

where:

a. ΔQ is the quantity of heat supplied to (or removed from) the material.

b. L is the *latent heat* associated with the transformation in question, e.g., L_f (the latent heat of fusion), L_v (the latent heat of vaporization) or L_s (the latent heat of sublimation).

c. Δm is the mass of material which underwent a transformation of state [liquid to its solid state (fusion) or into its vapor state (vaporization); or the transformation of solid directly into vapor (sublimation)].

2.3 Rate of Heat Flow

If we apply a temperature gradient to an object; one is kept hot and the other end cold then heat flows from hot to cold. The heat flows through the surface of the object, into it at the surface in contact with the hot reservoir, and out of it at the surface in contact with the cold reservoir. The rate R (in calories/second or J/s) at which heat flows through the substance is given by:

$$R = \left(\frac{kA}{\Delta x}\right)\Delta T \qquad (3)$$

Where k is its thermal conductivity [e.g., for Styrofoam, k = 6×10^{-5} cal/(cm-°C-s)], A is the area of the material through which the heat transfer takes place, Δx is its thickness, and ΔT is the temperature difference ($T_{\mathbf{hot}}$ - $T_{\mathbf{cold}}$).

2.4 Determination of the Specific Heat of Aluminum

2.41 In the Temperature Range of -195.8 °C to 20 °C

In the first part of this experiment, the specific heat of aluminum is measured by immersing an aluminum cube of known mass m_{Al} and initial temperature $T_{i,Al}$ (**-195.8 °C**) into water of known mass m_w and initial temperature $T_{i,w}$, and measuring the final common equilibrium temperature T_f. If there is no loss or gain of heat energy from the environment by the water or the aluminum, the heat gained by the aluminum will be equal to the heat lost by the water,

$$\Delta Q_{Aluminum} = -\Delta Q_{Water}$$

Where the minus sign indicates that heat is flowing out of the water and into the aluminum cube. Applying the principle of the conservation of energy and using Eq. (1), one obtains the following equation applicable to this part of the experiment.

$$m_{Al}\bar{c}_{Al}(T_f - T_{i,Al}) = m_w\bar{c}_w(T_{i,w} - T_f) \qquad (4)$$

Solving for the specific heat one obtains:

$$\bar{c}_{Al} = \frac{m_w\bar{c}_w(T_{i,w} - T_f)}{m_{Al}(T_f - T_{i,Al})} \qquad (5)$$

2.5 Determination of the Latent Heat of Liquid Nitrogen

In this part of the experiment, the value of the latent heat of vaporization L_v of liquid nitrogen (**47.8 cal/g)** will be determined assuming the value of the specific heat of aluminum to be **0.17 cal/g-°C**.

This part of the experiment will involve the immersion of an aluminum cube at room temperature into liquid nitrogen and measuring the quantity Δm of the liquid nitrogen evaporated as the aluminum cube cools to the temperature of liquid nitrogen (-195.8°C). Equating the amount of the heat energy transferred to liquid nitrogen by the aluminum cube to the heat energy required to evaporate Δm grams of the liquid nitrogen, one obtains:

$$L_v = \frac{\bar{c}_{Al}\, m_{Al}\,(T_{i,Al} - T_{f,Al})}{\Delta m} \qquad (6)$$

where:

L_v = Latent heat of vaporization (evaporation) of liquid nitrogen
m_{Al} = Mass of aluminum cube immersed into liquid nitrogen.
$\bar{c}_{Al}$ = Specific Heat of aluminum in the temperature range of 20.00°C to -195.8°C (**0.17 cal/g-°C**)
$T_{i,Al}$ = Initial temperature of the aluminum cube at room temperature.
$T_{f,Al}$ = Final temperature of the aluminum cube at the B.P.T. of LN_2 (-195.8°C).
Δm = Grams of liquid nitrogen evaporated by the immersion of the cube.

The accepted value of the latent heat of liquid nitrogen is $\boldsymbol{L_v}$ **= 47.8 cal/g**. In this part of the experiment, cups and cubes will be on both pans of the balance so heat conducting through the cups can be neglected once the cube is immersed into liquid nitrogen. The room is at a much higher temperature than liquid nitrogen, so heat will conduct through the cups. Using this method, with cups and cubes on both pans, is an example of an extremely important measurement technique where you balance out some undesired phenomenon in your measurement by making your measurement relative to a second system so that you cancel the effect of the undesired phenomenon.

2.6 Determination of the Rate of Heat Flow Through a Styrofoam Cup

In this experiment a double Styrofoam cup will be filled with the liquid nitrogen. Heat will flow from the outer surface of the cup, maintained at room temperature (~20.00 °C), to the inner surface which is maintained at the temperature of the liquid nitrogen (-195.8 °C). This heat flow will result in the evaporation of liquid nitrogen. This rate R is related to the evaporation rate $\Delta m/\Delta t$ (g/s) of the liquid nitrogen by:

$$R = L_v\left(\frac{\Delta m}{\Delta t}\right) \qquad (7)$$

Where L_v is the latent heat of vaporization of liquid nitrogen (47.8 cal/g).

The rate of heat flow through the Styrofoam cup is also given by Eq. (3). In addition, R is given by:

$$R = \Delta Q/\Delta t \;\; (cal/sec) \qquad (8)$$

3 Experimental Apparatus and Procedure

3.1 Experimental Apparatus

1 Celsius thermometers
2 Aluminum cubes
3 Water
4 Large double Styrofoam cups for water.
5 Clock
6 Double Pan balance
7 Liquid nitrogen
8 Small double Styrofoam cups for LN_2 and small single Styrofoam cups for cubes.

3.2 Procedure

3.2.1 Measurement of the Average Specific Heat of Aluminum in the Temperature Range -195.8 °C to 20 °C.

1. Determine the mass of the aluminum cube (m_{Al}). Place a paper clip on the right pan of the balance when making this measurement.

2. Place the aluminum cube in a Styrofoam cup containing liquid nitrogen ($T_{i,Al}$).

3. While the object is cooling, weigh the large double Styrofoam cup. Fill it with room temperature tap water (around 200 g) and weigh it again. Compute the mass (m_w) of the water in the cup.

4. Insert a thermometer into the cup with water, and measure the temperature of the tap water ($T_{i,w}$). Allow some time for the thermometer to come to thermal equilibrium with the water. **Do not** put the thermometer into liquid nitrogen as **this will destroy it**.

5. You will hear a **loud sizzling noise** from the cube when it is at thermal equilibrium with liquid nitrogen (LN_2). When you are ready to immerse the cube into the water, quickly remove the cube from the LN_2 and insert it into the cup with the water. **Be careful not to splash water from the cup**.

6. Begin stirring the water once the cube is in. Monitor the temperature. The temperature will fall to equilibrium. You may note that ice will initially form on the cube. When the system attains its lowest temperature, measure, and record, the final equilibrium temperature (T_f) of the water-aluminum cube system. The lowest temperature will be reached in a period of time after the ice melts, and when the cube and water are at thermal equilibrium. Allow sufficient time for this temperature to be reached.

3.2.2 Measurement of the Latent Heat of Vaporization of Liquid Nitrogen

1. Measure and record the mass (m_{Al}) of the aluminum cube which will be placed into liquid nitrogen. It is best to measure this cube again, as there may have been an error in the first measurement. Note this mass and compared it to when you measured it in 3.2.1. Comment on any difference in the mass measurements in your lab report. Differences in your measurements of the cube may reflect error in using the scale. Place a paper clip on the right pan when making this measurement. This will be the cube which will be placed on the **right pan** of the balance in this portion of the experiment.

2. Place a small single cup and a small double Styrofoam cup on both pans of the balance. Place aluminum cubes into the small single Styrofoam cups. The **right pan** should have the cube whose mass has been measured. A paper clip should be attached to the small cup on the left pan.

3. Reset the clock to 0 seconds. One student should operate the clock and the other should work with the scale balance.

4. Ask the instructor or TA to pour the liquid nitrogen. Fill both small double Styrofoam cups **approximately 3/4 full**. Use the spoon (transfer LN_2) to balance the scale to the equilibrium position. This should equal 0.00 grams on the scale.

5. As soon as the scale is at equilibrium, immerse the cube on the **right pan** into the liquid nitrogen cup on the **right pan**. **Be careful not to splash LN_2 out when immersing the cube**.

6. **Start the clock** as soon as the cube is immersed.

7. Observe the liquid nitrogen boiling vigorously because the aluminum cube, at its initial room temperature, is very hot relative to liquid nitrogen which is at -195.8°C. Heat flows rapidly from the cube into the liquid N_2, thus increasing the evaporation rate. It will take approximately 120 seconds for the immersed cube to come to thermal equilibrium with the liquid nitrogen. At this point, you will here a **loud sizzling noise** as the liquid nitrogen actually comes in contact with the surface of the immersed cube. Prior to thermal equilibrium, an envelope of nitrogen gas separates the liquid nitrogen from the immersed "hot" aluminum cube.

8. **Immediately** after the **loud** sizzling of LN_2 stops, **reset** the balance to equilibrium and **stop** the clock. Record this new equilibrium mass.

9. Record the time the cube took to come to thermal equilibrium, and the mass Δm.

3.2.3 Measurement of the Rate of Heat Flow *R*.

1. Place this **small double Styrofoam cup** on the **left pan** of the balance.

2. Reset the clock to indicate 0 seconds.

3. Move the mass sliders to 110 grams. Ask the instructor or TA to **pour approximately 110 grams** of liquid nitrogen into the **small double Styrofoam cup**. Fill the cup so that the balance just tips to the left. Now, move the mass to 108.00 grams. This mass will be recorded as your initial mass at time t = 0 seconds.

4. Observe that as the liquid N_2 in the cup evaporates, the balance pointer swings toward the right and eventually crosses the balance point (the center of the balance scale). At this instant of time, **and no other**, the total mass placed on the left pan is equal to the mass set in step 3 (108.00 grams). **Note:** You and your lab partner should work out the protocol to read and record the time when the balance pointer passes the balance point.

5. Start the clock and record the mass, 108.00 grams, as the pointer first goes through the equilibrium point. **<u>Once started, do not turn off the clock until the end of the experiment otherwise you will need to repeat this part of the experiment</u>**.

6. Reset the balance to indicate 2 grams less than the previous setting (now, 106.00 grams). Record the time when the pointer crosses the balance point.

7. Repeat step 6 eight more times for a total of 10 measurements (108.00 grams to 90.00 grams).

4 Calculations and Analysis of the Data

4.1 Computation of the Average Specific Heat of Aluminum in the Temperature Range of -195.8 °C to 20 °C.

Use Eq. (5) to determine the experimental average specific heat capacity $\overline{c}_{Al}$. Assume specific heat of water to be **0.998 cal/g-°C** in the vicinity of room temperature. The accepted value is $\mathbf{\overline{c}_{Al}}$ **= 0.17 cal/g-°C** in this temperature range. Calculate your percent difference in $\overline{c}_{Al}$.

4.2 Computation of the Latent Heat of Vaporization of Liquid Nitrogen in the Temperature Range of 20 °C to -195.8 °C.

Use Eq. (6), and $\mathbf{\overline{c}_{Al}}$ **= 0.17 cal/g-°C**, to determine the latent heat of vaporization of liquid nitrogen. The accepted value is $\boldsymbol{L_v}$ **= 47.8 cal/g**. Calculate your percent difference in L_v.

4.3 Computation of the Rate of Heat Flow *R* Through a Styrofoam Cup

4.3.1 Make a graph of your data from **3.2.3**. This should be a graph of mass vs time. Calculate the slope, $\Delta m/\Delta t$, of this graph. In the lab, use Excel, and for your report, use 18 cm x 25 mm graph paper.

4.3.2 **Use your calculator's linear regression function** to determine the slope and correlation coefficient of mass vs time data from **3.2.3**. This should also be in your lab report. Use your graph from **4.3.1** to determine which is the best linear data to enter into your calculator. The correlation coefficient, R or R^2, reflects the linearity of your data. The closer this value is to 1, the more linear is your data. The correlation coefficient from your calculator should also be presented in your lab report.

4.3.3 Using your slope of mass vs time from linear regression (**4.3.2**) and the accepted value of L_v for liquid nitrogen (**$\boldsymbol{L_v}$ = 47.8 cal/g),** calculate the rate of heat flow using Eq. 7. This value is also entered into your lab report.

5 Questions

1. List various factors, especially errors in measurement and experimental work, which might affect your value of the specific heat of aluminum for part **3.2.1**.

2. Explain why the heat flow through the cup is negligible in **3.2.1** but *not* in **3.2.2** and **3.2.3**.

3. In **3.2.3,** what is the direction of the heat flow? What can be done to reduce the heat flow between room temperature and a container of liquid nitrogen? Refer to Eq.(3) to help in this answer.

4. Use Eq. (2), and the accepted value of L_v, to calculate the amount of heat, in calories, required to evaporate the quantity of liquid nitrogen Δm in **3.2.2**. This evaporation is a result of the heat lost by the cube in the time it took to reach thermal equilibrium with LN_2.

5. During this time period in question 4, liquid nitrogen was also evaporating due to the transfer of heat into the cup from the surrounding room. Using your results from **4.3.3** (Eq. 7) and that $R = \Delta Q/\Delta t$

(calories/second), calculate the amount of heat, in calories, transferred into the cup during the time it took for the aluminum cube to come to thermal equilibrium in **3.2.2**.

6. Why are we able to neglect the flow of heat into the cup from the surrounding room when we calculate L_v in **4.2**?

6 Conclusion

This section should have a clear statement of the results of the experiment and the extent to which the results are in agreement with the theory being tested. When the experiment results in a measurement of a constant, e.g., the acceleration of gravity, g, compare it with its established handbook values. Use percent difference for this comparison. To make this comparison meaningful, you should include the impact of the experimental error on your results. This includes errors in plotting and reading linear graphs when determining their slope and intercept. In addition, please include a statement of what you have learned, a critique of the experiment, and any suggestions you have which you think could improve the experiment or the lab handout.

An Experiment on Heat
Data Sheets

3.2.1 Measurement of the Average Specific Heat of Aluminum in the Temperature Range -195.8 ^{o}C to 20 ^{o}C.

Mass of Aluminum (m_{Al}) =______________g

Mass of the Styrofoam cup =______________g

Mass of the Styrofoam cup plus water =______________g

Mass of the water (m_w) =______________g

Initial temperature of Water ($T_{i,w}$) =______________^{o}C

Initial temperature of Aluminum Cube ($T_{i,Al}$) =______________^{o}C

Final temperature of Water ($T_{f,w}$) =______________^{o}C

Final temperature of Aluminum Cube ($T_{f,Al}$) =______________^{o}C

3.2.2 Measurement of the Latent Heat of Vaporization of Liquid Nitrogen

Mass of Aluminum Cube (m_{Al}) =______________**g**

Initial Room Temperature of Aluminum Cube ($T_{i, Al}$) =______________**^{o}C**

Final LN_2 Temperature of Aluminum Cube ($T_{f, Al}$) =______________**^{o}C**

Time when LN_2 stopped boiling and Aluminum Cube

reached the LN_2 Temperature =______________**s**

Mass of LN_2 Evaporated =______________**g**

3.2.3 Measurement of the Rate of Heat Flow *R*.

Table I: Clock Time and Mass of LN_2.

Time t seconds	Mass g grams
	108.00
	106.00
	104.00
	102.00
	100.00
	98.00
	96.00
	94.00
	92.00
	90.00

Estimated error in reading balance. Error$_m$ = $\pm \Delta m$ = _______ g

Estimated error in reading thermometer. Error$_T$ = $\pm \Delta T$ = _______ ^{o}C